

# Energy–water nexus analysis in the Beijing–Tianjin–Hebei region: Case of electricity sector

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## ABSTRACT

Water shortage can constrain energy development and use, and climate change partially caused by energy consumption can profoundly affect the quantity and distribution of water resources worldwide. The chronic water shortage in the Beijing–Tianjin–Hebei region of China is likely to worsen under the impact of global climate change. The coal-dominated electricity sector will continuously have a high water demand. This reality will intensify the dilemma between water supply and power generation. This paper presents an adaptability analysis of the Beijing–Tianjin–Hebei region in 2013–2030 based on the current situation. Water evaluation and planning and long-range energy alternative planning systems are used to simulate changes in water and energy systems, respectively, and the impacts on the electricity sector under two climate scenarios and three development scenarios. On this basis, this study explores the potential of power structure adjustment and technological advancement in easing baseline water stress and promoting sustainable development in the region. Findings show that the Beijing–Tianjin–Hebei region is under high water stress, which will be aggravated under global climate change. In representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios, the baseline water stress of the region in 2017–2030 averages 259% and 494%, and the annual unmet water demand reaches 15.3 and 21.1 billion m<sup>3</sup>, respectively. In the renewable energy and advanced technology scenarios, the regional water savings are expected to reach 200–250 million m<sup>3</sup> by 2030. The unmet water demand of power generation can be alleviated to some extent, but the water shortage trend cannot be reversed. Therefore, the Beijing–Tianjin–Hebei region should develop an overall plan and layout of energy and water resources and adopt a combination of policy instruments to support the expansion of renewable energy or promote advanced power generation technologies.

## 1. Introduction

Energy and water are essential to human beings and inseparable from all aspects of human activities. These two basic resources are strongly related to human life and production. On the one hand, energy production, transportation, and utilization affect water resources. For example, coal mining, washing, transportation, and utilization affect the quantity and quality of water resources. On the other hand, water extraction, purification, and utilization entail energy consumption. Processes such as seawater desalination also involve high energy use [1].

The nexus between energy and water is currently facing new conditions and challenges beyond the traditional relations of influence and constraint. With mass fossil fuel consumption and continuous greenhouse gas (GHG) emissions, critical global climate change, the continuing rise in average global temperature, and frequent extreme

weather events have greatly transformed global hydrological systems and profoundly reshaped the global quantity and regional allocation of water resources. The deviation of hydrological systems exacerbates regional imbalances by adjusting the quantity of water resources in regions [2]. From the perspective of the energy–water nexus, the water inflow of hydropower stations and cooling water supply for thermal power plants will be adversely affected [3], while the variation in water resource distribution will remodel the energy use of water extraction and conveyance [1]. Power generation is a key entry point for energy–water nexus research. According to the *World Energy Outlook 2016* of the International Energy Agency (IEA) [4], energy and water are interdependent. Managing energy–water linkages is pivotal to the successful realization of various development and climate targets, in which power generation as a leading case needs critical attention.

With the increasing energy consumption that results from the rapid industrialization and urbanization in China, water shortage and

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imbalance have evolved into a major threat to the sustainable development of regional energy systems. Predictions also indicate that China may face more floods in the wet south and more droughts in the dry north. This potential situation could further aggravate the challenges brought by reverse energy and water distribution [5]. As a result, the water supply contradictions in water-stressed areas, such as the Beijing–Tianjin–Hebei region, will be significantly influenced, thereby limiting regional energy transformation.

The Beijing–Tianjin–Hebei region, which is known as China's capital area, encompasses Beijing, Tianjin, and Hebei Province and occupies 218,000 km<sup>2</sup>, which is equivalent to only 2% of the national land area. Its resident population reached 121.05 million in 2016, accounting for 8.1% of the national total. The regional gross domestic product (GDP) amounted to 7.46 trillion yuan, and the import and export volume reached 431.31 billion US dollars, representing 9.7% and 11.7% of the national total, respectively [6]. The Beijing–Tianjin–Hebei region is recognized as China's economic, political, cultural, and technological innovation center and, together with the Yangtze River Delta and Pearl River Delta, is considered China's most dynamic urban cluster. Over the years, regional development has been underpinned by high energy consumption. The regional electricity consumption in 2015 reached 467.41 billion kWh, 31% or 142.74 billion kWh of which came from external sources [7]. The regional water supply situation is also grim. The available water resources have always been insufficient to meet the high demand because water is sourced only from Haihe Drainage Basin and limited transferring water from Huanghe and South-to-North Water Diversion Project. The excessive exploitation of groundwater resources results in severe land subsidence [8]. Therefore, the Beijing–Tianjin–Hebei region faces more serious challenges in terms of energy and water resources.

The climate model of future global temperature rise reveals that the unmet water demand in the Beijing–Tianjin–Hebei region is expected to increase due to the worsening water shortage. The competition for water resources between the energy system, especially the power generation sector, and other sectors will intensify. Nevertheless, water savings could be realized through the potential optimization of energy mix and power generation technologies. Research on the role of the energy system in influencing regional water use and alleviating regional water stress under different policy and planning scenarios can guide the optimization and coordination of energy- and water-related policies in the region. Considering the Beijing–Tianjin–Hebei region and focusing on the power generation sector, this study applies quantitative models to analyze the energy–water nexus under different climate scenarios and develops an optimal electricity structure to alleviate water stress. This study will provide policy support for energy and water optimization and green and sustainable development of the Beijing–Tianjin–Hebei region.

## 2. Current research

The energy–water nexus has become an important field of research with the publication of the IEA's *World Energy Outlook 2012*, which dedicated a chapter to the energy–water nexus [9]. Numerous studies have since been conducted on the energy–water nexus from a systematic and macro-level perspective, such as energy–water interaction mechanism or quantitative effects on water resources brought by energy exploitation, transportation, and consumption and by energy consumption during water extraction, conveyance, and utilization.

According to the *World Energy Outlook 2016* [4], the energy sector was responsible for 10% of global water withdrawals, mainly for power plant operation and production of primary energy, and approximately 4% of global electricity consumption was used to extract, distribute, and treat water and wastewater. According to the Water in the West program co-funded by Stanford Woods Institute for the Environment [1], energy extraction, transportation, transformation, and consumption are accompanied by water depletion or water quality deterioration, but reverse circulation can be achieved through seawater desalination and sewage treatment to reextract water or improve water quality.

Energy use varies among phases in the water use cycle, including water source extraction, conveyance, water treatment, water distribution, and wastewater treatment. For example, the energy consumption for water extraction and conveyance involves seawater desalination, water transferring and water pumping.

Studies that adopt a micro-level perspective have increased as energy–water research widened its scope. Power generation, as the most intuitive component of the energy–water nexus, has drawn considerable attention. Lee et al. [10] chose urban water cycles as study field and surveyed 20 regions and 4 countries among the whole world. It is discovered that regions with higher water risks are always the ones have higher energy and GHG intensities associated with their water supply systems. It revealed the coherence between water shortage problems with energy consumption. Liu et al. [11] limited the scope of the study to America. Seven scenarios are used to estimate the future state-level electricity–water nexus under climate change and technology development. DeNooyer et al. [12] narrowed the study to Illinois state only. The study focused on power generation sector, especially thermal power plants. Considering macroeconomic development and climate change, a shift from coal to natural gas in the energy sector of Illinois was recommended. Applying advanced cooling process or moderating water prices were also suggested.

Aside from narrowing down the region, numerous in-depth studies have been conducted to examine the content of existing energy–water research and look deeply into water–energy nexus in specific sectors. For example, Marsh et al. [13] presented the mechanism of the physical connection between electricity and water on the basis of an in-depth discussion on water use and water intensity in electrical production and consumption and electricity use for water utilization in New South Wales, Australia. Wang et al. [14] chose electricity sector too, but they focused on the equivalent virtual water resources concurrent with electricity transmission between regions on easing the water stress. According to their study, 16.3 GL water resources were transformed to inland areas from coastal areas in China via the electricity transmission. Liu et al. [15] researched into the steel industry in China. The detailed framework of the influences caused by water, energy and emission during all the steps within steel producing process was built.

Tools and methodologies for studies on the energy–water nexus have also increased. Existing methodologies are not limited to qualitative description. Mo et al. [16] used IO-LCA model produce a research about the energy consumption in portable water supply system from life circle analysis perspective. Hu and Ou, et al. [17,18] adopted Sankey diagram to illustrate economic, demographic, and energy flows over time and applied this research tool in industrial production to describe runoff of water resources in production and treatment in China; they also analyzed energy consumption in human-involved process. By adopting an input–output method, Gu et al. [19,20] systematically analyzed China's energy–water policy synergies during the 11th and 12th Five-Year Plan (FYP) periods, measured the direct and total energy/water consumption in industrial sectors, and estimated the energy and water savings derived from policies in such sectors as ferrous metals and petrochemicals. Stockholm Environment Institute (SEI) [21] integrated the self-developed Water Evaluation and Planning System (WEAP) and Long-range Energy Alternatives Planning System (LEAP) to examine the impact of a desalination project in California on local energy systems and water resources; SEI also proposed an analytical framework for the practical evaluation of energy, water, and emission impacts. The proposed framework also applies to energy–water nexus analysis of general projects. CGE model was integrated to the water–energy nexus study too, when economic influences were considered. Zhou et al. [22] used CGE model to simulate the impacts of energy tax on water withdrawal and consumption and energy consumption process. They proved the coherence between water and energy policies and called for co-management of water sector and energy sector.

The energy–water nexus has become a hot topic in the area of addressing climate change and energy system analysis. The literature

review demonstrates that energy and water are correlated in the entire process from extraction to consumption. Highlights of studies on energy–water nexus include physical coupling relationship, especially water used and consumed for the production and consumption of main energy varieties and energy used to extract, distribute, and purify water in different areas, and policy design and analysis that regards energy and water as an organic whole to promote the application of energy–water nexus in regional planning and environmental policy.

### 3. Models and methodology

This study integrates the WEAP and LEAP models to analyze and simulate the status and trend of the energy–water nexus in the electricity sector of the Beijing–Tianjin–Hebei region. LEAP in particular is used to simulate energy consumption and electricity sector development under economic and social development scenarios. By contrast, WEAP is used to simulate water supply under climate change scenarios. The WEAP–LEAP integrated module is applied to analyze and measure the gap between water supply and demand under different temperature rise scenarios and to further describe future water scarcity of the electricity sector and the energy–water nexus trend in the region.

#### 3.1. WEAP model

WEAP is an SEI-developed tool for regional hydrological modeling and water resource planning, and has been applied in more than 170 countries worldwide [23]. The GIS-based model simulates water resources in a region on the basis of water balance principle and evaluates the supply of rainfall, runoff, base flow, and groundwater with respect to the water demand of various sectors.

In the Beijing–Tianjin–Hebei region, water resources can be divided into the following three parts: (1) dynamic bodies, such as surface runoff, and transferred water; (2) static bodies, such as groundwater and reservoir water; (3) demand bodies, such as cities and parks. After identifying such forms, the water resource distribution can be described for a given period. Precipitation and evaporation are automatically converted into water resources in the dynamic and static bodies in the quasi-static study with month as the time interval. Thus, the dynamic process does not need to be described. The equation for water balance in the region can therefore be written as follows [24]:

$$S = S_{runoff} + S_{underground} - S_{overlap} + R_{transfer} \quad (1)$$

$$D = D_{con} + D_{non-con} + D_{sea} + \Delta R_{reservoir} + \Delta R_{underground} \quad (2)$$

$$S = D \quad (3)$$

where  $S$  is the total water supply in the region each year,  $S_{runoff}$  is the surface water supply,  $S_{underground}$  is the groundwater supply, and  $S_{overlap}$  is the overlapping supply of surface water and groundwater.  $R_{transfer}$  indicates the annual transferring water inflow from the Yellow River or the South-to-North Water Diversion Project to the region.  $D$  denotes the annual regional water depletion,  $D_{con}$  is the annual consumptive water depletion,  $D_{non-con}$  is the annual non-consumptive water depletion,  $D_{sea}$  is the annual runoff to the sea through the estuary,  $\Delta R_{reservoir}$  represents the amount of reservoir water storage, and  $\Delta R_{underground}$  is the amount of groundwater storage.

With the balance between supply side and demand side, WEAP model is able to predict the influence caused by the changes at one side to another. In this study, the input of WEAP model is the water supplement influenced by climate scenarios. Optimized by the model, the water resources are distributed to different demand sectors. Comparing the distribution to the prediction of water consumption, the unmet water demand in different sectors is determined.

This study sets four demand sites. Except regional demand points like Beijing, Tianjin, and Hebei, power generation is specially separated for further analysis and the integration to LEAP model. As for the

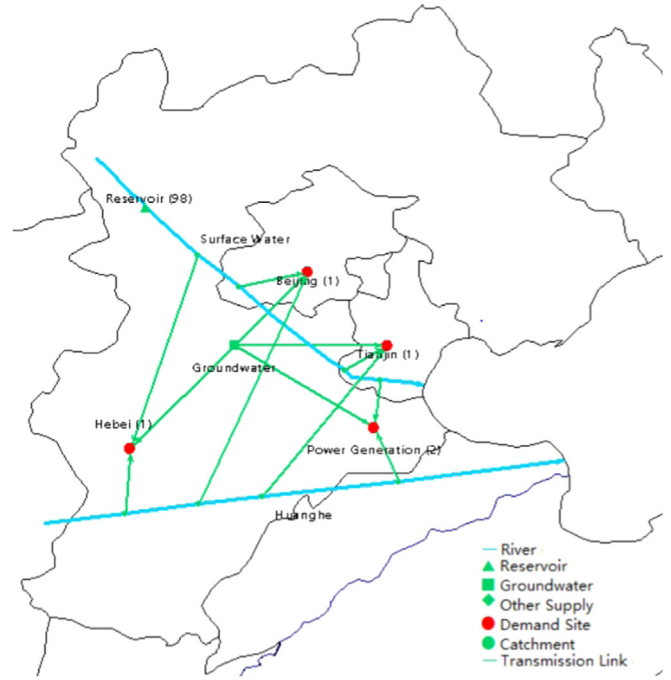


Fig. 1. WEAP model for the Beijing–Tianjin–Hebei region.

supply sites, four supply points namely, surface water, groundwater, reservoir, and hydropower stations are formed. One special setting in the WEAP model is that hydropower stations are on supply side rather than demand side. Because in the model, hydropower stations are considered as functional reservoirs. The settings of supply and demand points in WEAP model are shown in Fig. 1.

#### 3.2. LEAP model

LEAP is an SEI-developed tool for comprehensive energy system planning [25]. This tool can be used to describe a region's energy consumption driven by various factors, such as population, economy, technology, and price, and to measure the energy balance and GHG emissions under different scenarios. The LEAP-based logic for measuring energy consumption in a sector can be represented by Eq. (4) and (5) as follows:

$$C_i = \sum_r \sum_j A_{r,j} \times F_{r,i,j} \quad (4)$$

$$E_{CO_2} = \sum_i C_i \times E_i \quad (5)$$

where  $C_i$  is the consumption of energy  $i$ ,  $A_{r,j}$  is the activity level of energy in sector  $j$  in region  $r$ , and  $F_{r,i,j}$  is the intensity of energy  $i$  in sector  $j$  in region  $r$ , and the sum represents the total consumption of energy use sectors in all regions. Different sum has different meaning. For example,  $C_{i,r}$  represents the total consumption of energy  $i$  in region  $r$ . This variable acts as the key linkage between LEAP model and WEAP model in the integration part.

This study categorizes energy into coal, oil, natural gas, electricity, and heat, and divides consumers into the primary, secondary, tertiary, and household sectors, covering Beijing, Tianjin, and Hebei, i.e.,  $r = \{\text{Beijing, Tianjin, Hebei}\}$ ,  $j = \{\text{primary, secondary, tertiary, household}\}$ , and  $i = \{\text{coal, oil, natural gas, heat, electricity}\}$ . After base-year data calibration on the basis of an energy balance sheet along with regional energy development strategy and policy guidance, this study uses LEAP to measure the end-use consumption of different energy varieties in Beijing, Tianjin, and Hebei under the baseline scenario of economic development and population growth. This study then predicts the power structure of the region as a whole and the

development trend of each power generation sector.

### 3.3. WEAP–LEAP integrated model

To probe the interaction between energy and water systems, WEAP and LEAP are linked by key energy–water conjunctions. Actually, WEAP model can help evaluate how the suppliers would fit the region's future water needs and LEAP will show the impacts on energy demand. If the energy demand increases significantly, LEAP can help to explore options for meeting that demand. WEAP could help determine how much water needed in this region. Such is the cycle of exploration and discovery that this integrated WEAP–LEAP model enables. Using this model, we can explore how individual water or energy management have impact on both the water and energy systems, also understand tradeoff that might not be apparent when looking at either system alone.

From WEAP to LEAP, hydroelectric generation is the key link. In WEAP model, hydroelectric power generation are predicted. Then the result was fed to the LEAP model as the amount of hydropower generation in electricity mix. From LEAP to WEAP, the water consumption of electricity sector is the key linkage. In LEAP model, water intensities of different technologies could be set up as parameters. With the energy mix predicting results in LEAP model, water demand in different electricity generation sector could be calculated. In integration model, this demand is input into the WEAP model as the water demand of power generation sector. In this way, the descriptions of water and energy sources by WEAP and LEAP, respectively, can be successfully linked to simulate the energy–water system interaction.

### 3.4. Indicators of water supply

To evaluate the degree of balance in water supply and demand in the region, the study introduces baseline water stress (BWS) [26], as shown in Eq. (6).

$$BWS_i = \frac{WU_i}{WUU_i} \quad (6)$$

where  $WU_i$  represents the annual regional water consumption,  $WUU_i$  is the available water resources in the region, and  $i$  is the year.  $BWS < 20\%$  denotes low or moderate water stress,  $20\% < BWS < 80\%$  for moderate to high level of water stress,  $80\% < BWS < 100\%$  for high water stress that needs special attention, and  $BWS > 100\%$  for severe water shortage and water deficit, which implies that continued water extraction will destroy the regional hydrologic system.

For visual purposes, the reciprocal value of baseline water stress is set to indicate the water demand satisfaction degree of power generation ( $S$ ), as shown in Eq. (7).

$$S_i = \frac{EWUU_i}{EWU_i} \quad (7)$$

where  $EWU_i$  denotes the annual regional water consumption for power generation, and  $EWUU_i$  is the available water resources for power generation in the region.  $S < 100\%$  means that the available water resources do not satisfy the water demand, suggesting that the electricity sector must compete for water with other sectors.

## 4. Data sources and treatment

### 4.1. Data sources

The study area covers three administrative regions, namely, Beijing, Tianjin, and Hebei Province. On the basis of the caliber and availability of historical data for economy, society, energy, and water, the base year is set to 2013, and the scenario simulation is continued to 2030. Table 1 presents the raw data.

### 4.2. Scenario design

Climate models can significantly affect surface runoff, runoff generation, precipitation, and evaporation in a region. Two Representative Concentration Pathway (RCP) scenarios, namely, RCP 4.5 and RCP 8.5 [27], defined in the Fifth Assessment Report of Intergovernmental Panel on Climate Change are chosen. In this study, RCP 8.5 provides an extreme estimation and RCP 4.5 shows an average perspective. Combining with three future electricity scenarios in the Beijing–Tianjin–Hebei region, namely, Business as Usual (BAU), Renewable Energy (RE), and Advanced Technology (AT), a matrix containing 6 composite scenarios is formed. The data of water resources under different climate scenarios come from the output of land surface model coupled with the CLM–Mosart model by CESS, in which CLM (Community Land Model) was derived from Dai [28] in 2013 and Mosart (Model for Scale Adaptive River Transport) from Li [29] in 2013 and coupled with CLM. The climate data are the average results of projections made by the National Center for Atmospheric Research using 36 global climate models [30]. Table 2 presents the scenario design.

### 4.3. Data treatment and basic assumptions

#### 4.3.1. Level of economic and social development–GDP, industrial structure, and population

The economic data in the study are converted to constant 2013 prices. The GDP growth rates of Beijing, Tianjin, and Hebei in 2016–2030 are expected to reach 118.6%, 128.3%, and 84.8%, respectively. Considering the local industrial policy and regional development plan outline, the share of primary, second, and tertiary industries by 2030 will change to 0.22%, 19.50%, and 80.27% in Beijing; 0.68%, 51.29%, and 48.04% in Tianjin; and 5.91%, 48.14%, and 45.95% in Hebei, respectively.

The population changes in Beijing, Tianjin, and Hebei are estimated according to the latest research of the United Nations World Population Prospects 2015 [31] combined with Beijing's 13th FYP for population control. The regional population is expected to peak during the 14th FYP period and gradually decrease thereafter. The resident pollution in the region will reach 118 million in 2030, which is an increase of approximately 7 million compared with that in 2015.

#### 4.3.2. Water consumption

Considering the predicted level of economic activities, relevant policy guidance, and water conservation effects over the years, the comprehensive water intensity in Beijing will improve insignificantly, but a considerable improvement will occur in Tianjin and Hebei due to industrial application of water-saving technologies and slowdown of agricultural development. The WEAP model estimates that the water demand in the Beijing–Tianjin–Hebei region will steadily decrease, and the water use structure will change dramatically with the fast decline in agricultural water intensity and rapid increase in ecological water intensity.

#### 4.3.3. End-use energy consumption

The energy data in this study are converted into coal equivalent. The predicted level of economic activities indicates that the end-use energy consumption of the Beijing–Tianjin–Hebei region will reach approximately 600 million tons of coal equivalent (tce) by 2030, considering the national energy strategy and regional energy plan. The regional energy structure is also examined on the basis of economic and social development, specific energy consumption, and policy requirements. Heat and oil will maintain a relatively stable share in the energy mix, while the share of coal will decline rapidly. Natural gas will complement the generated energy gap. Electricity consumption is influenced by complex factors, such as transformation of the economic structure from secondary to tertiary industry, improvement of residential living standards, and emergence of novel electrical equipment

**Table 1**  
Raw data and sources.

| Category            | Primary data                                                                                                              | Sources                                                                                                                                                                                                        |
|---------------------|---------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Economy and society | GDP structure of the country and the Beijing–Tianjin–Hebei region in 1990–2015                                            | National Statistical Yearbooks and Local Statistical Yearbooks                                                                                                                                                 |
|                     | Resident population of China and the Beijing–Tianjin–Hebei region in 2000–2015                                            | National Statistical Yearbooks and Local Statistical Yearbooks                                                                                                                                                 |
| Energy              | Amount and structure of primary energy consumption and end-use energy consumption in the country in 2000–2015             | National Bureau of Statistics (NBS), National Energy Administration (NEA), and Energy Statistical Yearbooks                                                                                                    |
|                     | Amount and structure of end-use energy consumption in the Beijing–Tianjin–Hebei region in 2013                            | Energy Statistical Yearbooks                                                                                                                                                                                   |
| Water               | Power generation and operation hours of generating units of the country and the Beijing–Tianjin–Hebei region in 2011–2015 | National Energy Administration, China Electricity Council, Compilations of Statistics for Electricity Industry, and China Hydropower Yearbooks                                                                 |
|                     | Water resources, water consumption, and the structure of the Beijing–Tianjin–Hebei region in 2004–2015                    | Local Statistical Yearbooks                                                                                                                                                                                    |
|                     | Water resources, runoff, groundwater, and reservoir storage of the Haihe Drainage Basin in 2013–2015                      | Haihe River Water Resources Bulletins, Annual National Water Reports, and Haihe River Management Committee of Tianjin                                                                                          |
|                     | Water intensity of thermal power units with different technical combinations                                              | Evaluation indicator system for cleaner production of the electricity industry (coal-fired power companies), Greenpeace, and energy-efficiency benchmarking and competition data on 300 MW thermal power units |
|                     | Changes of surface runoff and runoff production in Haihe Drainage Basin in 2006–2030 in different climate models          | Center for Earth System Science (CESS) at Tsinghua University and the CLM–Mosart model                                                                                                                         |

**Table 2**  
Scenario design.

|         |         | Electricity                                                                                                                                  |                                                                                                                                                                           |                                                                                                                          |
|---------|---------|----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
|         |         | BAU <sup>a</sup>                                                                                                                             | RE                                                                                                                                                                        | AT                                                                                                                       |
| Climate | RCP 4.5 | Global average temperature rise of 2.4 °C <sup>b</sup> , and electricity sector development in accordance with the current policy objectives | Global average temperature rise of 2.4 °C, proportion of renewable energy increased by 10% points (5% points each for wind and solar power) over the BAU scenario in 2030 | Global average temperature rise of 2.4 °C, supercritical air-cooled units for all coal-fired units introduced after 2016 |
|         | RCP 8.5 | Global average temperature rise of 4.3 °C, and electricity sector development in accordance with the current policy objectives               | Global average temperature rise of 4.3 °C, proportion of renewable energy increased by 10% points (5% points each for wind and solar power) over the BAU scenario in 2030 | Global average temperature rise of 4.3 °C, supercritical air-cooled units for all coal-fired units introduced after 2016 |

Note:

<sup>a</sup> The combination of BAU and RCP 4.5 is hereafter referred to as BAU-4.5. The method is applicable to the rest of the combinations.

<sup>b</sup> The global average temperature rise refers to the rise of the global average annual temperature by 2100 compared with that recorded during the pre-industrial period.

**Table 3**  
Energy end-use structure of the Beijing–Tianjin–Hebei region by 2030.

|         | Coal   | Oil    | Natural gas | Heat <sup>a</sup> | Electricity <sup>b</sup> |
|---------|--------|--------|-------------|-------------------|--------------------------|
| Beijing | 3.29%  | 22.5%  | 15.85%      | 5.43%             | 52.93%                   |
| Tianjin | 15.74% | 27.19% | 15.17%      | 7.13%             | 34.77%                   |
| Hebei   | 39.99% | 8.36%  | 6.88%       | 5.83%             | 38.94%                   |

Notes:

<sup>a</sup> The equivalent method is used to calculate the heat consumption.

<sup>b</sup> The electricity consumption is calculated according to coal consumption for electricity supply.

(such as electric vehicles). Table 3 shows the end-use energy consumption by 2030.

#### 4.3.4. Power supply structure

The electricity consumption in the Beijing–Tianjin–Hebei region is dominated by thermal power and dependent on external power. Considering regional development planning and national and regional policies, the regional hydropower capacity will be stable. The additional installed capacity will be derived from clean and renewable energy, such as natural gas, wind, solar, and biomass. The installed capacity of wind and solar power in 2030 will increase by approximately 35 and 50 million kW comparing to 2015, respectively. The operation hours for power generation will remain stable, and the share of renewable energy in the electricity mix will increase to 18%. Thermal and external power will account for 56% and 26% of the remaining demand, respectively.

## 5. Scenario analysis results

### 5.1. End-use energy consumption

The LEAP results of end-use energy consumption in the Beijing–Tianjin–Hebei region in 2013–2030 are based on the basic assumptions about regional economic and social development and on regional energy development trend and policy planning, as shown in Figure 4.6. End-use energy consumption in the region in 2030 will total 589 million tce, which is an increase of 159 million tce compared with that in 2013. Of the total end-use energy consumption, 91, 116, and 382 million tce will be consumed by Beijing, Tianjin, and Hebei, respectively. Coal and natural gas will account for 174 and 58 million tce, respectively, and electricity consumption will reach 741.6 billion kWh, implying higher electrification level and larger clean energy share. (Fig. 2)

### 5.2. Water supply and demand

The CLM–Mosart simulation results of water supply in the Beijing–Tianjin–Hebei region differ significantly under the RCP scenarios. In the RCP 4.5 scenario, water resources amount to 12.91 billion m<sup>3</sup> on average in 2013–2030, which is 13.1% less than the multi-year average. The water resources are relatively abundant in 2014, 2022, and 2026, and they are relatively scarce in 2018 and 2027. In the RCP 8.5 scenario, the water resources reach 8.21 billion m<sup>3</sup> in 2013–2030, which is approximately two-thirds of the level in the RCP 4.5 scenario and 44.7% lower than the multi-year average. In relative terms, the wet

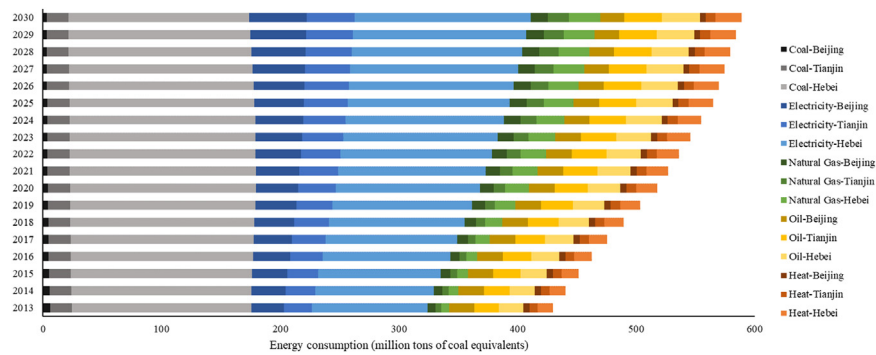


Fig. 2. End-use energy structure of the Beijing–Tianjin–Hebei region (2013–2030).

years are 2022 and 2023, and dry years are 2015, 2016, 2020, and 2021.

The WEAP simulations of water demand and deficit indicate insignificant change in water scarcity in the Beijing–Tianjin–Hebei region and highest water unmet demand in Hebei. The water demand of this area could be satisfied only in an extremely abundant year such as 2026. The water demand in the region will decline steadily, reaching 23.24 billion  $\text{m}^3$  by 2030, of which the water demands of Beijing, Tianjin, and Hebei account for 5.90, 3.37, and 13.97 billion  $\text{m}^3$ , respectively. In the RCP 4.5 scenario, the unmet water demand in the region will expand to 7.94 billion  $\text{m}^3$  by 2030, which implies 4.41, 1.67, and 1.86 billion  $\text{m}^3$  of unmet water demand in Beijing, Tianjin, and Hebei, respectively. In the RCP 8.5 scenario, the regional unmet water demand is 14.86 billion  $\text{m}^3$ , which is considerably higher than that of the RCP 4.5 scenario; the unmet water demands of Beijing, Tianjin, and Hebei contribute 5.09, 2.44, and 7.34 billion  $\text{m}^3$ , respectively. The future water supply is predicted to continue to rely considerably on groundwater overexploitation. To satisfy the unmet water demand, the groundwater overexploitation will amount to 150–210 billion  $\text{m}^3$  in 2017–2030, which will result in far-reaching hydro-ecological impacts and destruction.

Fig. 3 illustrates the BWS results of the WEAP–LEAP integrated model. In the BAU scenario, the baseline water stress in the region is generally high. In the RCP 4.5 scenario, the baseline water stress averages 206% in 2013–2030. All the years, except the abundant year 2026, are facing a baseline water stress of more than 134%, which suggests that the supply failed to satisfy the demand by at least 34%. In the RCP 8.5 scenario, regional water availability is limited, and the average baseline water stress reaches 319%, indicating prominent water supply contradictions as water demand is nearly three times that of available water resources.

### 5.3. Water demand satisfaction for power generation

In the severe water situation, the electricity sector of the Beijing–Tianjin–Hebei region will face considerable water pressure.

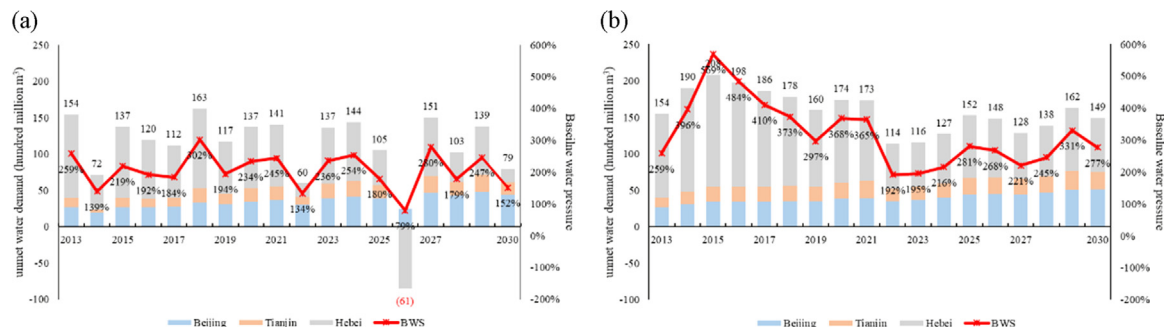


Fig. 3. Baseline water stress in the Beijing–Tianjin–Hebei region (2013–2030). (a) RCP 4.5; (b) RCP 8.5.

Fig. 4 shows the unmet water demand and water demand satisfaction in the BAU scenario. In the RCP 4.5 context, the annual average unmet water demand in 2013–2030 expands to 474.1 million  $\text{m}^3$ , which means that only 53.7% of the water demand is satisfied on average. In the RCP 8.5 context, the average unmet water demand increases to 672.5 million  $\text{m}^3$ , while the percentage of satisfied water demand decreases further by 34.3%. This result implies that the electricity sector may be forced to compete with downstream residents and ecosystems for water.

In the RE scenario, the water demand of the electricity sector decreases with thermal power generation. The WEAP–LEAP simulation results show that by 2030, the proportion of renewable energy for power generation in the region will increase to 28.3%, contributing to a reduction of approximately 50 million  $\text{m}^3$  in annual water demand. Water conservation effectiveness will improve as the installed capacity of wind and solar power expands over time. By 2030, additional water savings derived from renewable energy will reach 210 million  $\text{m}^3$ , which is equivalent to 31.2–44.3% of the unmet water demand of the electricity sector under the BAU scenario. The annual average degree of water demand satisfaction in the energy sector can be improved by 36.1–56.5% from the BAU-scenario level of 34.3–53.7%.

In the AT scenario, the water intensity of thermal power generation drops significantly as all new coal-fired units are supercritical and air-cooled units. The WEAP–LEAP simulation results show that compared with the BAU-scenario level, the average water demand satisfaction in 2013–2030 rises from 53.7% to 62.5% in the RCP 4.5 context and from 36.1% to 40.2% under the RCP 8.5 context. The significance of the water-saving effect will improve over time, and the effect will reach 250 million  $\text{m}^3$  by 2030, which is equivalent to 37.1–52.7% of the unmet water demand of the electricity sector under the BAU scenario.

Fig. 5 depicts the details of water demand satisfaction of the electricity sector under different combined scenarios. The water demand is better satisfied in the AT scenario than in the RE scenario mainly because high amounts of water savings are derived from technological advances in the large thermal power base in the Beijing–Tianjin–Hebei region.

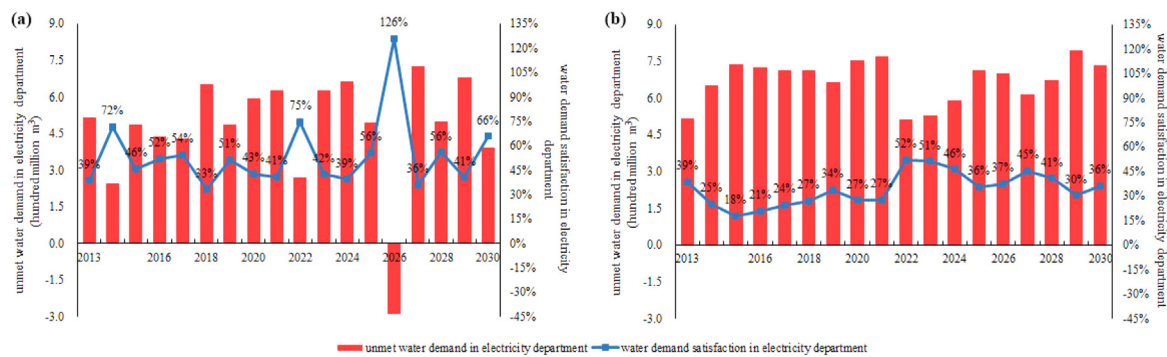


Fig. 4. Water deficit and water demand satisfaction in the electricity sector under different scenarios. (a) BAU-4.5, (b) BAU-8.5.

## 6. Conclusions and discussions

Energy consumption in the Beijing–Tianjin–Hebei region along with economic and population growth will continue to increase, although at a slow rate. The total regional end-use energy consumption is expected to reach 589 million tce by 2030, and the annual growth will reach 2.8%, 1.8%, and 0.8% during the 13th, 14th, and 15th FYP periods, respectively. Under the dual impact of national energy revolution strategy and regional eco-environmental treatment, the end-use energy mix will change considerably in 2013–2030, presenting low-carbon, clean, and electrification trends. Coal consumption is expected to peak during the 14th FYP period and gradually decline in the next five years. The electrification level is also expected to improve gradually. The electrification level in Beijing, Tianjin, and Hebei will increase to 52.9%, 34.8%, and 38.9% by 2030, respectively. The per capita electricity consumption in Beijing will exceed 7000 kWh/year, which is equivalent to the current level of medium-sized cities in developed countries. Renewable energy will account for 18.2% of electricity production in the region, and clean energy will become an integral part of such production. On the basis of these data, the carbon emissions per unit of GDP in the region in 2020 and 2030 are estimated to decline by 47–50% and 61–66%, respectively, from the 2005 level, thereby exceeding the intended nationally determined contributions.

Groundwater overexploitation serves as a supplement to the water overabstraction in the region. Predictions suggest that the regional contradictions between water supply and demand will be further exacerbated by global climate change and average temperature rise. Even under the current policy restraint, the annual regional unmet water demand in 2017–2030 will reach 10.9 billion m<sup>3</sup> in the RCP 4.5

scenario and 15.0 billion m<sup>3</sup> in the RCP 8.5 scenario. The region will have to intensify groundwater exploitation to address water requirements, which will aggravate the hydrological situation and water shortage. This study does not consider the full influence of the South-to-North Water Diversion Project, because it is not fully operational yet at the base year 2013. If the project can contribute to the water supply of Beijing–Tianjin–Hebei Region as planned, then the project could provide approximately 5.7 billion m<sup>3</sup> of water annually, which may cover 38.0–52.3% of the unmet demand and alleviate the intense pressure on groundwater resources.

The electricity sector exhibits potential resilience to the future effects of climate change as renewable energy development and promotion of water-saving technologies can ease the water pressure to a certain extent. Water savings will hit 210 and 250 million m<sup>3</sup> by 2030 in the RE and AT scenarios, respectively. However, the water shortage trend in the electricity sector and the water shortage condition in the energy sector can be eased but not erased. As the water consumption of the electricity sector is considerably less than that of the agricultural sector, water shortage in the region as a whole is irreversible.

To promote energy–water coordinated development, the Beijing–Tianjin–Hebei regional strategies should integrate the overall plan and layout of energy and water resources, analyze potential resources and utilization forms from a holistic perspective, and link energy use and water use at supply and demand sides. On the supply side, adequate energy resources should be transformed to water resources without undermining water supply for the energy sector, such as through implementation of regional seawater purification and wastewater treatment projects, to fundamentally resolve regional water shortage. Reclaimed water along with desalination in Beijing and

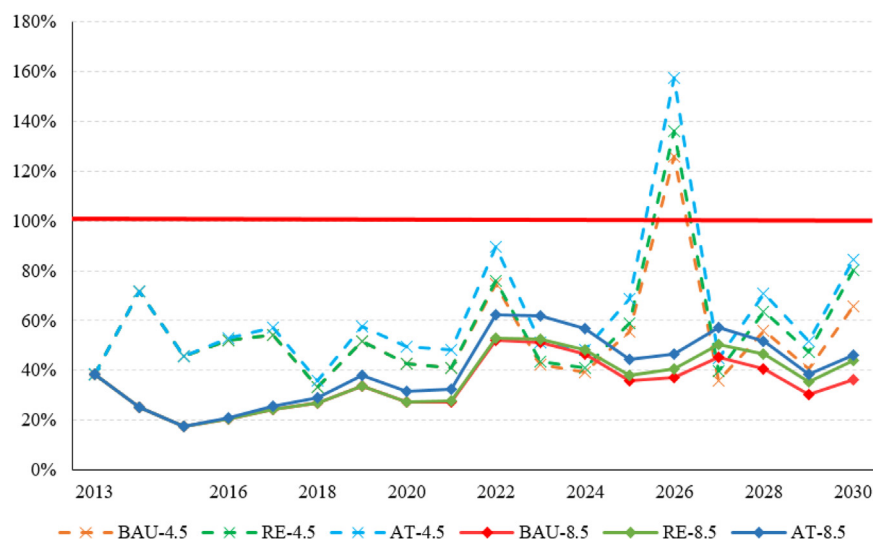


Fig. 5. Water demand satisfaction in the electricity sector under different scenarios (2013–2030).

Tianjin has already contributed significantly to the water supply, whereas the share of Hebei remains insignificant. The use of recycled water in the region should be improved to ease the water shortage stress. On the demand side, the Beijing–Tianjin–Hebei region should accelerate economic restructuring and develop high-value-added strategically emerging industries represented by the modern service industry. A combination of policy instruments, such as tax breaks and research projects, is recommended to support renewable energy and water-saving technologies for power generation and thereby reduce water demand. The transformation of the regional power system into a renewable energy-oriented one will not only effectively control air pollution but also reduce water consumption. As to the existing thermal power units, the penetration of water saving technologies and air cooling systems will be conducive to the water efficiency of the coal and electricity sectors and will be effective in reducing the unmet water demand in the energy sector. Some emerging industries, such as the modern service industry, have high electricity demand and low water intensity, and show more flexibility in electricity and water use. These emerging industries can be more actively involved in real-time scheduling and market trading, and its substitution effect will help crowd out the regional mode of extensive development and further tap the potential of energy savings.

Although this study aims at Beijing–Tianjin–Hebei region specially, it could be instructive to other regions facing similar problems. Highly urbanized, densely populated regions share the concern that energy sector may scramble water resources with other sectors. Meanwhile, climate change as a global fact may affect this contradiction worldwide. The study in Beijing–Tianjin–Hebei region is a representative warning to all regions under potential threat.

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